In situ measurements of near-surface hydraulic conductivity in engineered clay slopes

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Abstract

In situ measurements of near-saturated hydraulic conductivity in fine grained soils have been made at six exemplar UK transport earthwork sites: three embankment and three cutting slopes. This paper reports 143 individual measurements and considers the factors that influence the spatial and temporal variability obtained. The test methods employed produce near-saturated conditions and flow under constant head. Full saturation is probably not achieved due to preferential and by-pass flow occurring in these desiccated soils. For an embankment, hydraulic conductivity was found to vary by five orders of magnitude in the slope near-surface (0 to 0.3 metres depth), decreasing by four orders of magnitude between 0 and 1.2 metres depth. This extremely high variability is in part due to seasonal temporal changes controlled by soil moisture content (up to 1.5 orders of magnitude). Measurements of hydraulic conductivity at a cutting also indicated a four orders of magnitude range of hydraulic conductivity for the near-surface, with strong depth dependency of a two orders of magnitude decrease from 0.2 to 0.6 metres depth. The main factor controlling the large range is found to be spatial variability in the soil macro structure generated by wetting/drying cycle driven desiccation and roots. The measurements of hydraulic conductivity reported in this paper were undertaken to inform and provide a benchmark for the hydraulic parameters used in numerical models of groundwater flow. This is an influential parameter in simulations incorporating the combined weather/vegetation/infiltration/soil interaction mechanisms that are required to assess the performance and deterioration of earthwork slopes in a changing climate.

Keywords: Hydraulic conductivity, engineered fill, field measurement, near-surface

Infrastructure slopes are complex structures made up of a composite of soil, water, air and vegetation. The mechanical and hydraulic properties of the *in situ* (cuttings) and compacted (embankments) materials play a controlling role in the stability of earthwork slopes (O'Brien, 2013). The UK experiences infrastructure slope failures that have primarily been triggered by changes in soil hydrology due to rainfall (e.g. Springman *et al.* 2003; Xue & Gavin 2007; Hughes *et al.* 2009; Glendinning *et al.* 2014; Briggs *et al.* 2016). Slope instability causes significant disruption to the UK's road (Anderson & Kneale 1980; Garrett & Wale 1985) and rail (Loveridge *et al.* 2010; Ridley *et al.* 2004; Birch & Dewar 2002) networks. Large numbers of slope failures were recorded during periods of high precipitation in the winters of 2000, 2001, 2007, 2014 and summer of 2012. Cyclic seasonal effects, potentially influenced by a changing climate, also impact on slope structures. Dry summer periods remove water that leads to shrinkage and cracking; prolonged and intense rainfall events cause swelling and increased pore water pressures (Loveridge *et al.* 2010; Hughes *et al.* 2009; Smethurst *et al.* 2012; Briggs *et al.* 2013; O'Brien 2013; Glendinning *et al.* 2014). Repeated shrink-swell cycles can lead to accumulation of shear strains resulting in strain softening and progressive failure (O'Brien *et al.* 2004; Vaughan *et al.* 2004; Loveridge *et al.* 2010; Take & Bolton 2011; O'Brien 2013). The spatial and temporal distribution of hydraulic conductivity of the soil (this term has been used with the same meaning as coefficient of permeability) governs the distribution, magnitude and rate of change of pore water pressures within a slope. The size and distribution of these pore water pressure cycles, and hence effective stress cycles, control the progressive failure mechanism. For example, soil with higher hydraulic conductivity, although still low compared to coarse grained soils, can lead to more rapid and larger changes in pore water pressure and effective stress at depths (Nyambayo *et al.* 2004; O'Brien *et al.* 2004; O'Brien 2013), promoting progressive failure of a slope, often after many years of stability (Briggs *et al.* 2016). Knowledge of hydraulic conductivity and how it varies with depth and over time is therefore needed if the movement of water and its influence on slope stability is to be quantified.

Flow conditions in the near-surface of engineered slopes are both complex and transient. Wetting and drying weather cycles coupled with the influence of vegetation roots, result in the formation of a weathered mantle in the order of a few metres thick. This zone has a soil macro structure from desiccation cracking and roots that produces preferential flow conditions (Smethurst *et al.* 2012). Water enters the slope by infiltration of rainwater and is removed by evaporation and evapotranspiration processes. The availability of water in this near-surface zone controls the degree of saturation and the hydraulic conductivity with depth, and hence the magnitude of soil suction/positive pore water pressures and the magnitude and frequency of effective stress cycles.

The challenge is to measure soil parameters that can be used to describe the flow conditions under these changing conditions (i.e. changing degree of saturation).

Hydraulic conductivity of a fine grained soil is controlled predominantly by the pore geometry and water content, which in turn controls the degree of saturation and magnitude and distributions of suctions (Rose 1966; Boynton *et al.* 1985; Brady & Weil 1999). Lower initial degrees of saturation lead to higher initial flow rates as water is taken into storage. Successive increases in degree of saturation then decrease the pore water suction gradients and decrease flow into the soil (Lili *et al.* 2008). In partially saturated conditions, hydraulic conductivity can be obtained through measurement of soil water retention behaviour (i.e. the Van Genuchten-Mualem model that gives the relative hydraulic conductivity against suction or saturation/water content for a given Soil Water Retention Curve (van Genuchten 1980)). However, this aspect of behaviour is not covered in the current paper. At depth and during periods of prolonged rainfall the soil can become, or approach, saturated conditions and this controls the movement of water into and within the slope for significant periods of the year. The aim of the study described in this paper is to measure the hydraulic conductivity under these saturated, or near-saturated, conditions.

Water introduced into a clay slope during a test to measure hydraulic conductivity will be under a low hydraulic head and coupled with the micro structure of the soil (e.g. clay blocks/peds separated by desiccation cracks and penetrated by roots) this will result in bypass (i.e. preferential) flow where an enhanced flux follows cracks, root channels and other connected meso and macro-pore channels. As a consequence of the relative short duration of the tests it must therefore be assumed that in the zone affected by the test the centre of the peds will not become saturated. Therefore, measured values of hydraulic conductivity reported in this paper should be considered near-saturated values representing the bulk hydraulic conductivity of predominantly bypass flow, with a minor contribution from matrix flow in the soil pores through the edges of the peds. These soil conditions are comparable to those developed in slopes through infiltration of rain water during wet periods and hence are still relevant and important for the study of slope behaviour.

Numerous methods have been developed for field and laboratory determination of soil hydraulic conductivity. Testing methods in field conditions include the Guelph permeameter (Reynolds & Elrick 1986; Youngs *et al.* 1995; Kannangara & Sarukkalige 2011); single and double ring infiltrometers (Dyer *et al.* 2008; Li *et al.* 2011); the tension disc permeameter (Angulo-Jaramillo *et al.* 2000); and falling head permeameters (Merva 1987). Permeameters based on measured inflow into a zone of soil beneath the ground surface have become common practice and used with some success to determine soil hydraulic conductivity (*k*) for agriculture, hydrology and geotechnical engineering applications.

Soil macro structure features such as cracks, fissures and sand lenses control the hydraulic conductivity of fine grained soils at the near-surface as discussed above. Laboratory tests provide hydraulic conductivity (k) values that tend to increase with increasing sample diameter, as soil macro structure features are statistically more likely to be present in large soil volumes compared to small (Boynton & Daniel 1985; Li *et al.* 2011). In the laboratory, common methods include flexible wall permeameters (Daniel *et al.* 1984), constant and falling head rigid wall permeameters (Mohanty *et al.* 1994), and consolidation cell permeameter tests. These methods often yield dissimilar results as measurements are sensitive to sample size, hydraulic boundary conditions, flow direction and soil physical characteristics (e.g. density and degree of saturation). However, despite these limitations, laboratory tests are often favoured for determining hydraulic conductivity in fine grained soils as they are a quicker and cheaper alternative to *in situ* tests. Despite this, retrieval of undisturbed samples can be problematic with cracking and changes in soil density occurring during core recovery (Hight 2000). Side wall leakage can be a problem in laboratory permeameters (i.e. preferential flow rates at the interface between the soil and permeameter wall can be orders of magnitude greater than the soil), and bypass flow due to the presence of worm or root holes can influence the results (Mohanty *et al.* 1994; Youngs *et al.* 1995). The critical limitation is that typical samples sizes of 70-100mm diameter are often too small to capture the bulk hydraulic conductivity that is controlled by soil fabric.

Field (*in situ*) hydraulic conductivity measurements avoid some of the problems described above. However, despite a range of field equipment types and test methods being available for measuring hydraulic conductivity, no single method is satisfactory for all conditions. Measurements in fine grained soils have historically been considered problematic due to the large number of tests often required to characterise heterogeneity and to the extended times taken to establish steady flow condition and hence useable data (Lee *et al.* 1985; Daniel 1989; Mohanty *et al.* 1994; Nagy *et al.* 2013). Problems also arise from the inability of some test systems, such as the double ring, to measure hydraulic conductivity effectively on slopes.

Hydraulic conductivity plays an important role in the behaviour of slopes formed in fine grained soils (e.g. O'Brien 2013), however, current uncertainty regarding the reliability and usefulness of commonly used *in situ* measurement techniques, justifies a review of available approaches and reporting of systematic studies of field hydraulic conductivity. *In situ* measurement techniques are required that can be used to determine representative values of hydraulic conductivity at specific sites, depths and times. These can then be used in on-going studies to understand and model the time dependent stability of engineered slopes in fine grained soils (Glendinning *et al.* 2014; Glendinning *et al.* 2015). This paper reports an investigation of hydraulic conductivity at a number of exemplar UK infrastructure sites primarily using two of the most commonly used field methods, the Guelph Permeameter and the Double Ring Infiltrometer (DRI). It considers the benefits and limitations of the methods for characterising the near-surface hydraulic conductivity of engineered slopes formed in fine grained soils, and details ranges of values to be found in such slopes. This research forms part of the EPSRC funded project called Infrastructure Slopes Sustainable Management and Resilience Assessment (iSMART) (Glendinning *et al.* 2015).

Field methods

Only a few studies in the literature have explored the application and effectiveness of field methods to measure near-surface hydraulic conductivity in fine grained soils forming engineered slopes (e.g. Dyer *et al.* 2009; Loveridge *et al.* 2010). This current study concentrates on the application of two commonly used field methods for *in situ* materials: Guelph permeameter and double ring infiltrometer. Brief details of the two methods are provided below.

Guelph Permeameter

The Guelph Permeameter (Reynolds & Elrick 1986) is an in-hole constant-head permeameter, employing the Mariotte principle to measure flow rates. The method measures the steady-state flow rate Q (m^3/s) necessary to maintain a constant depth of water H (m) in an uncased cylindrical well of radius a (m), at the test soil depth. Under steady state flow conditions, field saturated hydraulic conductivity k_s (m/s) is calculated using two or more measured pairs of Q and H for each test location with radius a, using the approximate analytical solution (Equation 1) proposed by Reynolds & Elrick (1986). C is a dimensionless shape factor primarily dependent on the H/a ratio relating to the soil type being tested.

$$\begin{aligned} Q &= \left(\frac{2\pi H^2}{C} + \pi a^2\right) k_s + \frac{2\pi H}{C}\phi_m \\ &= A k_s + B\phi_m \end{aligned} \qquad (1)$$

Q = Steady state flow (m^3/s)

H = Well head depth (m)

a = Well radius (m)

C = Shape factor – relating to soil type

ϕ_m = Soil matric flux potential (m^2/s)

k_s = hydraulic conductivity (m/s)

Soil matric flux potential represents a short-term absorption factor and is described in detail by Reynolds & Elrick (1986). The double-head procedure as used in the current study is considered the most accurate (Reynolds & Elrick 1985). When a constant well height of water is maintained in a cored hole in the soil, a bulb of 'saturated' soil with specific dimensions is established; noting that soil in the near-surface may not be saturated at commencement of a test. The bulb, its shape and the time required are dependent on the type of soil (i.e. hydraulic conductivity), the radius of the well and head of water in the well. The unique bulb shape is established when the outflow of water from the well reaches a steady-state flow rate, which is measured (Fig. 1a). The rate of this constant outflow of water, together with the diameter of the well, and height of water in the well can be used from two or more tests at a location to determine the field near-saturated (i.e. reflecting the possibility of by-pass flow as discussed above) hydraulic conductivity (k_s) of the soil using Equation 1.

Double Ring Infiltrometer

The double ring infiltrometer measures hydraulic conductivity of the surface soil, and consists of an inner and outer ring inserted into the ground. The double ring method works by directing water onto a known surface area within the inner ring. The rings are installed 100 mm into the soil minimising disturbance of the soil to form a seal. The outer ring allows water in the centre ring to flow primarily vertically downwards, creating a (near) saturated, one dimensional flow condition (Fig. 1b). Each ring is supplied with a constant head of water either manually or from Mariotte bottles. Hydraulic conductivity can be estimated for the soil when the water flow rate in the inner ring reaches a steady state. When a steady infiltration rate is achieved (taken as 3 to 4 readings of similar values) the soil is assumed to be at or close to a saturated condition and the hydraulic conductivity of the soil (k_s) in the vertical direction is calculated using D'Arcy's (1856) relationship (Equation 2).

$$k_S = Q / i \, . \, A \qquad (2)$$

Where k_S is the 'saturated' hydraulic conductivity (m/s), Q is the infiltration rate within the inner ring (m^3/s), i is the hydraulic gradient (taken as a value around 0.2 based on pore water pressure/suction measurements below some of the ring experiments described below) and *A* is the cross-sectional area of the inner ring (m^2).

A small number of single cell constant head tests are also reported. These use a square in plan cell with dimensions 100 x 100 mm installed in the same way as the ring infiltrometers. The low head in the cell (typically 50 mm) is kept constant using a float connected to a pump, with the volume of flow obtained by weighing the water entering the cell to maintain the constant head. Calculation of hydraulic conductivity is based on the same approach as for the Guelph permeameter.

Field sites

Hydraulic conductivity has been measured at six UK sites (Fig. 2). The sites form a network of exemplar engineered slopes that have been monitored over a number of years by the collaborating partners within the iSMART group (http://www.ismartproject.org/). These sites include road and railway cuttings and embankments formed in six different fine grained soils and with different ages and established vegetation. A total of 143 tests are reported in this paper: 97 in embankments and 46 in cuttings. Summary details of the sites and information on the type, number and conditions for the tests are given in Table 1.

Site descriptions: Embankments

BIONICS Embankment (Northumberland, UK)

Newcastle University and collaborators constructed an artificial embankment research facility in 2005 located at Nafferton Farm, near Stocksfield, Northumberland (Ordnance Survey grid reference NZ 064 657). This has been engineered to form sections with variable properties (i.e. using Highway Agency standard compaction specification and also poorly compacted sections representative of older earthworks) and is extensively instrumented to monitor slope response to weather sequences. The embankment consists of Durham Lower Boulder Clay, a Glacial Till sourced from an industrial development to the east of Durham, and is underlain by stiff to hard Glacial Till to a depth in excess of 16 m underlain by Carboniferous Sandstone. The 6 metre high embankment has 22 degree slopes vegetated with grasses and the crest of the embankment is capped with a layer of coarse free draining material. A full description of the site, construction and instrumentation can be found in Hughes *et al.* (2009). In the period 2009 to 2014 a total of 85 tests to measure hydraulic conductivity were conducted on the side slopes, primarily using Guelph permeameters. The majority of tests were conducted in the zone 0.2 to 0.6 metres below ground level (m.b.g.l.) with a smaller number at depths to 1.4 m.b.g.l.. Key variables at this site are: degree of fill compaction (well and poorly compacted sections) and slope aspect ratio (north and south facing).

Charing (Kent, UK)

A Gault Clay fill Network Rail embankment located in the South East of England (Ordnance Survey grid reference TQ 302 805) was monitored by Mott MacDonald between June 2007 and July 2008, and 4 Guelph hydraulic conductivity tests were conducted (Briggs 2010). It has a foundation of Gault Clay underlain by Folkestone Beds. The upper part of the embankment consists of tipped industrial ash. The embankment was constructed in ~ 1874 and is up to 8m high with typical slope angles of between 18 and 25 degrees. The slopes were vegetated with shrubs and mature trees including Oak, Hawthorn, Willow, Silver Birch and Elm trees. Details of the site can be found in Briggs (2010).

Laverton (Gloucestershire, UK)

Laverton railway embankment, forms part of the Gloucester and Warwickshire heritage railway and is located to the north east of Cheltenham (Ordnance Survey grid reference SP 067 360). It has been monitored by a consortium of British Geological Survey, Queens University Belfast and University of Bath since July 2013 (Bergamo *et al.*, 2016). The railway was originally part of the Great Western Railway's Cheltenham–Stratford-upon-Avon–Birmingham line, known as the Honeybourne Line, and was built between 1900 and 1906. The Laverton embankment is around 5 m high with 28 degree slopes and is believed to have been constructed by end tipping of local Charmouth Mudstone. The side slopes were vegetated with mature trees and bushes, which were removed from the embankment slopes in October 2014 (after the infiltration tests). The upper layer of the embankment comprises 0.9 m of ballast fouled with fines and soil (rich in humus). A total of 8 hydraulic conductivity measurements are reported for this site from 2013 comprising both Guelph and double ring tests.

Site descriptions: Cuttings

Newbury (Berkshire, UK)

Newbury highway cutting is located on the A34 in Southern England (Ordnance Survey grid reference SU 463 562) and is being monitored by University of Southampton. The cutting was constructed in 1997 in London Clay. The London Clay at the site is about 20 m thick, highly weathered to a depth of about 2.5 m below original ground level, and underlain by Lambeth Group deposits and the Upper Chalk. The 8 m metre high 16 degree slope is vegetated with grasses and shrubs. A detailed description of the site can be found in Smethurst *et al.* (2006, 2012). Soil moisture content, pore water pressures/suctions, and weather have been monitored at the site since 2003. A total of 23 tests have been conducted to measure hydraulic conductivity using Guelph, double ring, bail out tests (e.g. rising head tests) and a small number of single ring constant head tests, all in the period 2003 to 2015.

Loughbrickland (County Down, Northern Ireland)

Loughbrickland road cutting is located 10 miles north of Newry, County Down, Northern Ireland (Ordnance Survey grid reference SB 205 983) and is being studied by Queen's University Belfast. It was constructed in 2004 as part of the A1 dual carriageway upgrade, which is a major arterial route. Loughbrickland is located within Drumlin swarms and consists of glacial/lodgement till overlying Silurian Greywacke/Shale. The slope is 24 m high with a 25 degree average slope angle vegetated with grasses and shrubs. Further site details, information on the monitoring since 2004 and analysis can be found in Hughes *et al.* (2016), Carse *et al.* (2009) and Harley *et al.* (2013). A total of 12 Guelph hydraulic conductivity measurements are included in this study.

Craigmore (County Down, Northern Ireland)

Craigmore railway cutting is located just outside Newry, County Down, Northern Ireland (Ordnance Survey grid reference SB 156 886) and is being monitored by Queen's University Belfast. The cutting is approximately 150 years old, and is excavated through stiff glacial till overlying granite. The 16 m high 36 degree slope is vegetated with grasses and shrubs. Further site details, information on the monitoring since 2007 and analysis can be found in Carse *et al.* (2009) and Harley *et al.* (2013). A total of 11 Guelph hydraulic conductivity measurements are included in this study.

Site specific test conditions

There are no guidelines for *in situ* tests on fine-grained materials (i.e. k_s <10^{-7} m/s) using the methods employed in this study. ASTM (1998) reports that these (i.e. Guelph and Double ring infiltrometer) methods should typically be used in soils with hydraulic conductivity in the range 10^{-3} to10^{-6} m/s. This is due to the extended time of testing required to establish steady state flow conditions in low hydraulic conductivity soils and the potential errors that can be introduced measuring the associated very low flow rates. However, Baumgartner *et al.* (1987) have demonstrated that the test method is feasible and an appropriate technique for use in clay fills, with measured k_s values as low as 10^{-9} m/s, and this justifies use of the selected methods. In this study, measurements have been made over a variety of timescales at the sites, with experiments being conducted over a period of hours (e.g. BIONICS, Laverton, Loughbrickland and Craigmore), days (e.g. BIONICS) and weeks (e.g. Newbury) to establish steady state flow conditions. The number of measurements recorded to establish steady state is also variable with between 5 to 14 observations being made and used to calculate hydraulic conductivity values.

Measured hydraulic conductivity

Fundamental differences between micro and macro structures of materials forming embankment fill slopes and cutting slopes makes it invalid to combine and compare hydraulic conductivity measurements, although comparison of trends and measurement techniques is valid. The results are therefore presented and discussed in two sections: embankments and cuttings. Table 2 summarises the mean, maximum, minimum and standard deviation of hydraulic conductivity for each site where there is a sufficient number of tests to warrant this analysis.

Embankment slopes

Spatial variability

All the measured hydraulic conductivity values from this study at the BIONICS, Laverton and Charing sites are plotted against depth in Fig. 3. For BIONICS, the tests conducted in the well and poorly compacted sections are also differentiated. The most significant trend shown in Fig. 3 for BIONICS is the very large variability in hydraulic conductivity in the uppermost 1 metre. Below 1 metre depth there are a smaller number of data points with lower variability and therefore to date, there is still limited data to indicate how variability may change with depth at this site. Although the number of measurements available for Laverton and Charing are limited in number, the groups of values for the three sites should be associated with the origin of the soils from which they are formed (i.e. BIONICS Glacial Till, intermediate plasticity; Laverton Charmouth Mudstone, high plasticity; and Charing Gault Clay, intermediate to high plasticity and potentially contaminated with sand rich local formations such as the Greensand), the age of the embankment, method of construction and vegetation history (e.g. Charing is more heavily vegetated). The small number of values for Laverton and Charing coupled with the large number of factors that can influence measured hydraulic conductivity, as discussed below, make a detailed comparison impractical. While the data for Charing are inconclusive regarding depth relationship, with all three values having a small range over the top 0.8 metres, the Laverton hydraulic conductivity measurements indicate greater than four orders of magnitude reduction in the top 1 metre.

The higher hydraulic conductivity values for Laverton compared with the majority of the BIONICS measurements is indicative of a more open structure fill material, such that even though Laverton is formed from a relatively high plasticity clay, macro structures such as fissures, root paths, animal burrows and fill clods in a softened matrix are controlling fluid flow (e.g. O'Brien 2013 and O'Brien *et al.* 2004). The age of both Laverton and Charing embankments means that they would have been formed from poorly compacted fill, with an extended time period for development of macro structures in the near-surface. At Charing, comparable hydraulic conductivity to BIONICS was measured near to the surface (Fig. 3). However, the relatively small number of tests at Charing may mean that no statistical significance can be attached to this comparison given the high spatial variability observed at the other sites. The measurements presented in Fig. 3 for Charing are all less than 1m deep. Borehole falling and rising head tests from old clay rail embankments below 3m depth are presented in O'Brien (2013). These are within the range of 10^{-6} m/s to 10^{-9} m/s supporting both the observations of lower k_s at greater depths and a wide range of values depending on local conditions.

The large number of measurements made at BIONICS over an extended time and under a range of conditions allows consideration of both spatial and temporal effects on hydraulic conductivity. The boundaries for the measured hydraulic conductivity measurements have an extreme spatial variability. Values in the top 0.8 metres have a range from $1\text{x}10^{-4}$ to $5\text{x}10^{-10}$ m/s (i.e. over five orders of magnitude) and there is also a marked trend of reducing hydraulic conductivity with depth: Maximum values decrease from $1\text{x}10^{-4}$ to $0.5\text{x}10^{-9}$ m/s (i.e. by over four orders of magnitude) between 0.2 and 1.4 m.b.g.l.. Considering the sets of measurements for the well and poorly compacted sections of embankment shown in Fig. 3, there is no significance difference (Table 2) although there is a tendency for the measurements in well compacted sections to be lower and for the poorly compacted hydraulic conductivity values to have a wider range as shown by the higher coefficient of variability (Table 2). This is consistent with the reduced control on the compaction process in the poorly compacted sections. When examining only the measurements made in 2009, Glendinning *et al.* (2014) show a significant and consistent influence of fill placement conditions, with the poorly compacted sections having a higher hydraulic conductivity at a range of depths (i.e. up to an order of magnitude). Including more data from different time periods has obscured this trend. Fig. 4 shows the BIONICS data re-plotted to denote the location of test positions relative to the West-East orientation of the embankment, which produces north and south facing slopes. Fig. 4 and the summary data in Table 2 indicate that having either a southern or northern aspect does not produce a clear difference in measured hydraulic conductivities, with both data sets demonstrating comparable magnitude of spatial variability noted above when considering well and poorly compacted sections. Again, when considering only the 2009 measurements, Glendinning *et al.* (2014) demonstrate that the southern slopes have a higher hydraulic conductivity by up to an order of magnitude and attribute this to the increased drying that results in desiccation and hence macro scale structures to form. The increased amount of data obtained over an extended period has obscured this trend. Although not shown in the figures presented, based on the available data there is also no appreciable difference in measured hydraulic conductivity related to the position of the test on a slope (i.e. crest, middle or toe), which may in part be a result of the test method producing near-saturated conditions as a function of establishing steady state flow under a constant head.

Temporal variability

A key factor when interpreting hydraulic conductivity measurements at shallow depths in fine grained soils is the influence of the initial moisture content established by antecedent weather conditions, which controls the degree of saturation, suctions and hence desiccation macro structures such as cracking. However, it must be noted that conducting a hydraulic conductivity measurement introduces water into the soil, which may initially be partially saturated, with the aim being to saturate a bulb of soil and establish steady seepage conditions. Thus some swelling will occur as steady flow conditions are established, although this cannot be measured, which will lead to changes in the macro structure and hence fluid flow properties (i.e. the test modifies the measured property). Where the time required to measure hydraulic conductivity is short relative to the typical rate of swelling of such fill materials then values will still reflect the soil conditions at the start of the test. Tests at BIONICS typically took a few hours, with some up to 24 hours, to establish steady flow conditions and this is short compared to the time required for complete swelling of the intermediate plasticity soil fill.

There are insufficient data for Laverton and Charing to consider temporal changes in hydraulic conductivity but the extended data set for BIONICS with measurement campaigns over a number of years means that temporal changes can be investigated. It would be expected that ‘near’ saturated hydraulic conductivity of the intermediate plasticity Glacial Till at a given plan location and depth will change over time; decreasing in periods of high moisture content (i.e. following periods of precipitation) and increasing when the moisture content is lower; noting that moisture content, degree of saturation and suctions are related through the soil water retention behaviour. Therefore, the timing of measurements in relation to antecedent weather conditions and hence time of year would be expected to have an influence. Fig. 4 shows the BIONICS data differentiated by year of measurement. Field campaigns were carried out in summer months (June to August) in the years 2009, 2010, 2013 and 2014, although the majority of measurements were made in 2009 and 2010. Measurements of near-surface volumetric water content (0.5 m.b.g.l.) and pore water pressures (0.5 m.b.g.l.) (Glendinning *et al.* 2014) made in the southern slope are presented in Fig. 5 and the timing of the field measurement campaigns are shown by the vertical bands. These indicate the soil conditions during the periods of hydraulic conductivity measurement. In both 2009 and 2010, hydraulic conductivity measurements were made during periods with initially low volumetric water content, which are assumed to equate to low degrees of saturation, and high pore water suctions. Saturation and pore water suctions then increase and decrease respectively during the measurement period as the soil wets up from the initial dry state as a combination of natural and artificially applied rainfall. The comparable conditions in the two periods is reflected in the similarity between the two sets of values (Fig. 4), although there is still the extreme variability as noted above, which in part will be a result of moisture conditions changing during the measurement periods in addition to spatial variability. Although there are only a smaller number of tests in 2013 and 2014 most of the measured hydraulic conductivity values are an order of magnitude lower than those measured in 2009 and 2010. In 2013 and 2014 the measurements were made at a time of zero suctions in the near-surface (although there is a developing drying trend in 2013), indicating high water contents and possibly saturated conditions (the volumetric water content measurements are discontinuous in 2013). These high water contents in the upper zone (0 to 0.5 m.b.g.l.) will result in swelling of the soil, closing of macro structures (e.g. preferential flow paths such as shrinkage cracks), and hence lower hydraulic conductivity.

To further investigate the influence of antecedent moisture conditions on hydraulic conductivity at specific locations, a number of repeat tests were conducted at the same location on the slope and depth before and following simulated rainfall events. A sprinkler system was installed on sections of both the southern and northern facing slopes to simulate intensive rainfall events. Fig. 6 shows changes in measured hydraulic conductivity in response to the simulated rainfall events in June to July both in 2009 and 2010. At the start of both experiments, large pore water suctions were measured using soil moisture sensors to determine the water potential representative of matrix suction (Fig. 5) and these measurements indicate that generally across the slope at the start of the sequence of hydraulic conductivity measurements the fill was dry and potentially desiccated with an inferred low degree of saturation. In 2009 the 10 day simulated rainfall amount was 220 mm and in 2010 the 23 day event was 367 mm. The rainfall values also include natural rainfall amounts. It can be seen that in all cases the hydraulic conductivity decreased by up to one and a half orders of magnitude, which is a result of rainfall infiltrating the near-surface, increasing the moisture content and degree of saturation of the soil, which swells and closes macro structures that provide preferential flow paths. The magnitude of change experienced at each location is variable, which is to be expected due to the small volume of soil influencing the test and variable local structure of the soil including desiccation cracking and root systems that will influence the magnitude and rate of changes in hydraulic conductivity as they close, as shown by Sinnathamby *et al.* (2014) in a study of a vegetated landfill cap. It should also be noted that each test alters the moisture conditions and degree of saturation at the test location as discussed above and this effect is incorporated in the observed behaviour on re-testing. However, the large changes in hydraulic conductivity measured following these prolonged periods of simulated precipitation demonstrate that swelling as a direct result of the water introduced during a test is probably a secondary effect. Also shown in Fig. 6 is a time series of 6 tests conducted at one location before, during and after the simulated rainfall event in 2010. Consistent with the other tests during this period, these show a progressive reduction in hydraulic conductivity of greater than one order of magnitude as the fill achieves increasing water content and degree of saturation.

Of the 85 hydraulic conductivity tests reported for BIONICS, 80 were made using the Guelph Permeameter and therefore the observed variability is not a function of test method. In addition, although four different operatives carried out the testing in 2009, 2010, 2013 and 2014, there is no indication of a bias in the values. In particular, the large data sets for 2009 and 2010 have the same range and degree of variability.

Cuttings

Spatial variability

All the measured hydraulic conductivity values from this study at the Newbury, Craigmore and Loughbrickland sites are plotted against depth in Fig. 7. The Craigmore and Loughbrickland slopes are formed in Glacial Till with Plasticity index ranges of 12 to 17 and 10 to 25 respectively. All measurements were made using the Guelph Permeameter. The two sites are similar but there are still differences as shown by the plasticity index ranges. Craigmore Till overlies granites and is more sandy and not as plastic, whereas the Loughbrickland Till overlies greywacke and is not as sandy. However, the measured hydraulic conductivity values are for the near-surface and these differences may not be significant. The slopes also differ in age. In Fig. 7 and Table 2 it can be seen that minimum values are comparable but Loughbrickland has mean and maximum values one order of magnitude higher than Craigmore. The data and trend lines in Fig. 7 show that hydraulic conductivities for the two sites have a similar range of three orders of magnitude between $1x10^{-7}$ to $1x10^{-4}$ m/s in the top 0.3 m.b.g.l. and at depths from 0.3 and 0.8 m.b.g.l. hydraulic conductivity values decrease by two orders of magnitude to between $1x10^{-8}$ and $1x10^{-7}$ m/s. The Newbury slope is formed in high plasticity London Clay. Hydraulic conductivity has been measured close to the surface using a double ring infiltrometer, Guelph permeameter and the single ring constant head apparatus. Fig. 7 shows a bi-linear relationship with no obvious depth dependency from ground surface to 0.3 m.b.g.l and values indicative of reducing hydraulic conductivity beneath this depth.

Between 0.1 and 0.3 m.b.g.l. the hydraulic conductivity values have a range of four orders of magnitude between $1x10^{-9}$ to $1x10^{-5}$ m/s. At 0.6 m.b.g.l., the range of measured values remains four orders of magnitude but shifts two orders smaller, following a similar trend of lower hydraulic conductivity with depth to the measurements for Loughbrickland and Craigmore. The lowest values of hydraulic conductivity measured at depth are as expected for *in situ* predominantly un-weathered London Clay (e.g. Chandler *et al.* 1990, Dixon and Bromhead 1999). Comparison of the trend lines for Newbury and Craigmore/ Loughbrickland cuttings shows differences in magnitude consistent with the properties of *in situ* London Clay and Glacial Till respectively, although rates of decrease with depth are similar.

Tests in the zone from ground surface to 0.3 m.b.g.l. have been made using three different methods, which allows comparison of the test methods (Fig. 8). The double ring infiltrometer (DRI) measured greater values of hydraulic conductivity than obtained from the Guelph and single ring apparatus. This may reflect the greater volume of soil measured using the double ring test (the inner ring of the DRI has plan area of 7 times that of the single ring apparatus used, and 35 times the plan area of the borehole used for Guelph measurements). The values of hydraulic conductivity measured at 0.6 m depth by the Guelph and single ring are consistent with laboratory values obtained using triaxial apparatus to conduct constant head tests on small 38 mm diameter samples (also plotted in Fig. 8); it is likely that these particular tests did not incorporate macro structures such as desiccation cracks. Also plotted in Fig. 8 are the results from two sets of bailout tests carried out in unlined boreholes about 3.0 m deep; values are plotted at mid-depth of lowest and highest water levels on the recharge curve. These measure mainly horizontal radial flow out of the borehole, and the larger values of hydraulic conductivity obtained (of about $5x10^{-9}$ m/s) are likely to be representative of larger structural features including thin silty bands encountered in the London Clay at Newbury (Smethurst *et al.* 2012). It can be concluded that the measured hydraulic conductivity may be a function of the method of measurement, with methods measuring a larger volume of soil likely to give greater values of hydraulic conductivity, particularly for a limited number of tests (there are few Guelph and single ring results for Newbury). The coefficient of variation for all three cutting sites is high (i.e. 1.9 to 2.6), which is indicative of the spatial variability of macro structures found in these natural materials further modified in the near-surface by vegetation roots and desiccation features.

Temporal variability

Loughbrickland values of hydraulic conductivity were made in July and August 2009 and Craigmore in the same period, and hence the sites will have been conditioned by similar antecedent weather conditions, which would have produced comparable soil moisture contents at the start of testing at the two sites. Therefore, the measurements do not allow consideration of temporal changes in hydraulic conductivity for these cutting slopes. At Newbury, the measurement campaign for the double ring and bail out test was March to September 2012 and double ring, Guelph and single ring constant head tests measurements were made in July 2014 and April to June 2015. Repeat tests were conducted at a specific plan location and depth of ~0.3 m.b.g.l. in 2012, 2014 and 2015. Concurrent with hydraulic conductivity tests, volumetric water content measurements beneath the slope were taken using moisture probes and at the same time using a Neutron Probe (Fig. 9) plotted as Soil Moisture Deficit following the methodology described in Smethurst *et al.* (2006). For comparison, Fig. 9 also plots the soil moisture deficit calculated from a simple water balance using site measured rainfall and evapotranspiration, again following the methodology given in Smethurst *et al.* (2006). In 2012 during March to August the volumetric water contents at 0.3 m depth were in the range 0.31 to 0.46 (note the bailout tests and DRI require measurements over periods of up to 4 weeks); Fig. 9 shows that 2012 was a wet summer with limited soil drying compared with others that are plotted such as 2011 and 2013. In July 2014 and in April to June 2015 when the later sets of hydraulic conductivity measurements were made, the soil conditions were similar, having relatively high moisture contents as a result of antecedent weather conditions (i.e. levels of rainfall). It is therefore not possible to gain knowledge on the influence of soil state (i.e. volumetric moisture content) on hydraulic conductivity from this study at Newbury. However, significant changes over time would be expected as the high plasticity London Clay will undergo large volume changes, and hence modifications to macro structure in the near-surface zone, as the moisture content cycles between weather driven maximum and minimum moisture contents.

Hydraulic conductivity trends

Factors influencing measured values of hydraulic conductivity can be categorized as either due to inherent material spatial and temporal variability, test boundary conditions or measurement error. Although it is seldom possible to separate the relative contribution of these factors, Phoon & Kulhawy (1999) report comparative studies of errors in laboratory strength tests on soil. Statistical analysis of results from a number of test programmes indicates that measurement errors for most laboratory strength tests, expressed in terms of coefficient of variation are in the range of 0.05 to 0.15. Inherent material variability results in coefficients of variation also of between 0.05 and 0.15 and the combined influence of measurement error and inherent variability is expressed by coefficient of variation of measured strengths between 0.07 and 0.21. However, there is a dearth of comparable information for these factors related to measurement of in situ hydraulic conductivity and in this study, measurement error is obscured by the many material influencing factors.

Table 2 reports coefficients of variation for the hydraulic conductivity measurements, with values of 2.20 to 4.26 for fill material (embankments) and 1.93 to 2.57 for the *in situ* materials (cuttings). These values are exceptionally high, being more than an order of magnitude greater compared to measurements for other soil parameters reported in the literature (e.g. Phoon & Kulhawy 1999). The wide range of hydraulic conductivity values measured in this study for a specific site is a function of three factors:

- Test method boundary conditions (e.g. volume of soil influencing measured behaviour and direction of flow in soil volume);
- Operator/test procedure including installation disturbance and errors identifying steady flow conditions; and
- Variability of the soil material in the volume subject to flow, including temporal changes in moisture content, degree of desiccation and discontinuities such as shrinkage cracks.

From the analysis of these factors for the BIONICS (Figs. 4 and 6) and Newbury (Fig. 7) data it can be concluded that test method (although soil volume size is a factor as discussed) and operator are secondary effects, and that spatial and temporal material variability is the primary cause of the measured variation of hydraulic conductivity in the slope near-surface. Further, the repeat tests at BIONICS (Fig. 7) demonstrate that while temporal changes in hydraulic conductivity due to moisture content changes can be significant (e.g. greater than one order of magnitude), spatial variability due to material and macro structure heterogeneity is the dominant factor.

A comprehensive study of hydraulic conductivity measurement and variability is reported by Deb & Shukla (2012) who investigated multiple factors. Their study focussed on measurements for agricultural applications that are controlled by soil-water-vegetation interactions at the near-surface and for very fine or silty sands with hydraulic conductivity values typically in the range 10^{-5} to 10^{-6} m/s. A summary of results from multiple studies gave coefficients of variation for field measurements of hydraulic conductivity typically in the range 0.5 to 1.0, but with some studies reporting coefficient of variations as high as 3.5. This large variability was considered to be a function of both spatial and temporal factors controlling the properties of the porous media such as structure, pore connectivity as well as properties of the fluid such as viscosity and temperature. It is not surprising that the field measurements of hydraulic conductivity in the fine grained soils reported in the present study have even higher coefficients of variation, because the intermediate to high plasticity of the soils result in moisture driven volume changes that generate highly heterogeneous macro structures. These structures will alter and evolve over time as the slopes are subjected to season cycles of wetting drying, and associated vegetation growth and die-back. These processes are less dominant in the predominantly silt and sand soils that form the core of data presented by Deb & Shukla (2012).

Influence of test method and operator

It is clear from previous studies (e.g. Deb & Shukla 2012; Nagy *et al.* 2013) that the test method will affect field measurement of hydraulic conductivity due to differences in zone (i.e. volume) of soil influencing the measurement, boundary conditions and direction of flow. This is also shown by the near-surface tests at Newbury discussed above. The larger volume of soil involved in the double ring infiltrometer tests may explain why the measured hydraulic conductivities are at the higher end (Fig. 8) due to greater tendency to incorporate macro features, cracks fissures etc. However, there is no evidence that the test method and operator can be used to explain the large range of hydraulic conductivity values measured in the current study. The test methods are well established and are mechanistic thus minimising the influence of the operator on values obtained. This is demonstrated by the BIONICS data sets for 2009 and 2010, both of which used the Guelph Permeameter but had different operators. There is no significant statistical bias in the two data sets that can be attributed to the operator, which cannot be explained by other factors of antecedent conditions, aspect and compaction.

The majority of studies in the literature considering the magnitude and variability of soil near-surface hydraulic conductivity have been for ecological and agricultural applications (e.g. Deb & Shukla 2012) and these typically involve soils with relatively high hydraulic conductivities 10^{-5} to 10^{-6} m/s compared to the materials that are the focus of the current study. The small number of studies that have explored the hydraulic conductivity of fine grained soils is explained by the recent emergence of interest in the controlling influence of the near-surface on long-term performance of engineered slopes (Glendinning *et al.* 2014; Smethurst *et al.* 2012; Springman *et al.* 2012). Another factor is the difficulties associated with the long periods of time often needed to reach steady state conditions in constant head tests. Measurements taken at Newbury in double ring infiltrometer tests used extended periods of time to record data (up to 28 days). Difficulties with logistics of consistent measurement recording over extended periods, particularly if logged measurement techniques are not available, and impacts of weather events during the measurement period changing the soil response can both be problematic.

Temporal and spatial variability

Although changes in hydraulic conductivity at a specific location with time are significant (Fig. 6), the range is orders of magnitude less than for the whole data set for each of BIONICS and Newbury. Therefore, differing antecedent conditions for a test cannot be used to explain the overall trend in values for these and, by extension, other embankments and cuttings formed in fine grained soils. However, there are still limited data available for location specific time series of measurements of hydraulic conductivity and further studies are required. It should also be acknowledged that conducting a test in an initially partially saturated soil, a condition common in the slope near-surface, introduces water into the volume of soil governing the measurement and hence this alters the moisture content regime, soil macro structure and thus value of hydraulic conductivity obtained.

An important finding of this study is that the hydraulic conductivity in an embankment formed in intermediate plasticity fine grained soil (i.e. BIONICS) can vary across the slope plan in the first 0.3 m.b.g.l. by up to five orders of magnitude. Hydraulic conductivity is also strongly depth dependent in the near-surface zone with up to four orders of magnitude decrease between 0.3 and 1.2 m.b.g.l.. For a cutting formed in high plasticity fine grained soil (i.e. Newbury), the variability in hydraulic conductivity at shallow depths (i.e. <0.3 m.b.g.l.) was found to be around four orders of magnitude, while the same strong depth dependency was found with two orders of magnitude decrease from 0.3 to 0.6 m.b.g.l.; although it should be noted that these trends are based on a smaller data set than for BIONICS. The depth dependency of 'near' saturated hydraulic conductivity within the soil profile is due to increased stress levels and reduced numbers and size of desiccation and vegetation features than are found near-surface (Boynton *et al.* 1985).

Conclusions

This study has for the first time investigated the application of standard and established methods for *in situ* measurement of 'near' saturated hydraulic conductivity for use in fine grained soils that form embankment and cutting slopes. There are many challenges to address when conducting such tests including the soil often being partially saturated at the start of the test, working on slopes, dealing with vegetation and the relatively long time (up to 28 days) to establish steady state flow conditions. The measurements reported in this paper are described as 'near' saturated because the macro structure of the near-surface soils investigated will result in by-pass flow through discontinuities that will leave partially saturated zones. However, despite this uncertainty in the degree of soil saturation, the reported hydraulic conductivity measurements are uniquely valuable. They are required for use in on-going research by the authors' as inputs for numerical models to help understand the interactions between weather, vegetation, infiltration and hence pore water and effective stress changes that influence the mechanisms and deterioration of infrastructure earthwork slopes.

Careful analysis of 143 *in situ* tests at six exemplar infrastructure sites has shown that:

1. The saturated hydraulic conductivity can vary by up to five orders of magnitude in the top 0.5m of infrastructure slopes. At greater depths within the slopes there is a pattern of decreasing hydraulic conductivity as well as decreasing variability.
2. The primary factor influencing the variability of hydraulic conductivity in engineered infrastructure slopes is spatial changes in materials and particularly material macro structure. This macro structure is dependent on construction methods and stress history as well as seasonal cycles, although temporal variation due to seasonal changes in moisture content and degree of saturation is secondary compared with overall spatial variability.
3. There is some influence of the test method on the hydraulic conductivity results, primarily related to the size of the zone being tested, with larger zones giving larger conductivity. However, again this factor is secondary compared to spatial variability. The influence of the test operator is minimal.
4. For *in situ* materials tested, higher plasticity stiff clays were seen to be of lower hydraulic conductivity compared with lower plasticity glacial tills.

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References

American Society for Testing and Materials 1998. Standard method D 5126 – 90 – Standard Guide for Comparison of Field Methods for determining hydraulic conductivity in the vadose zone, Annual Book of ASTM Standards 2001, Section 4: Construction, Vol. 04.08 Soil and Rock (I): D 420 – D 5779, 1055-1064.

Anderson, M.G. & Kneale, P.E. 1980. Pore water pressure and stability conditions on a motorway embankment. Earth surface processes, 5(1), pp.37-46.

Angulo-Jaramillo, R., Vandervaere, J.P., Roulier, S., Thony, J.L., Gaudet, J.P. & Vauclin, M. 2000. Field measurement of soil surface hydraulic properties by disc and ring infiltrometers. A review and recent developments. Soil Tillage Research, 55, 1–29.

Baumgartner, N., Elrick, D.E. & Bradshaw, K.L. 1987. In-situ hydraulic conductivity measurements of slowly permeable materials using a modified Guelph Permeameter and the Guelph Infiltrometer. Proc. of First National Outdoor Action Conference on Aquifer Restauration, Ground Water Monitoring and Geophysical Methods, May 18- 21, 1987, Las Vegas, Ohio, p.469-483.

Bergamo, P., Dashwood, B., Uhlemann, S., Swift, R., Chambers, J.E., Gunn, D.A. and Donohue, S., 2016. Time-lapse monitoring of climate effects on earthworks using surface waves. Geophysics, 81(2), pp.EN1-EN15

Birch, G. P. & Dewar, A. L. 2002. Earthwork failures in response to extreme weather. In Proceedings of the international conference railway engineering 2002, held in London, UK, July 2002-CD ROM.

Boynton, S.S. & Daniel, D.E. 1985. Hydraulic conductivity tests on compacted clay. ASCE Journal of Geotechnical Engineering. 111(4), 465–478.

Brady, N.C. & Weil, R.R. 1999. The Nature and Properties of Soils, 12th edition. Prentice-Hall: New Jersey; 879.

Briggs, K.M. 2010. Charing embankment: climate change impacts on embankment hydrology. Ground Engineering. 43(6), 28-31.

Briggs, K.M., Loveridge, F.A. and Glendinning, S., 2017. Failures in transport infrastructure embankments. Engineering Geology, 219, pp.107-117.

Briggs, K.M., Smethurst, J.A., Powrie, W. & O'Brien, A.S. 2013. Wet winter pore pressures in railway embankments. Proceedings of the ICE - Geotechnical Engineering 166, GE5, 451-465.

Carse, L., Mclernon, M., Hughes, D.A.B., Sivakumar, V. & Barbour, S.L. 2009. The magnitude and variation of pore pressures in glacial till slopes and their effect on slope stability. 62nd Canadian Geotechnical Conference, Halifax, September, Canadian Geotechnical Society, Editors: Lake, C. & Taylor, B, pp.6.

Chandler, R. J., Leroueil, S. & Trenter, N. A. 1990. Measurements of the permeability of London Clay using a self-boring permeameter. Géotechnique 40, 1, 113-124.

Daniel, D.E. 1989. In situ hydraulic conductivity tests for compacted clay. Journal of Geotechnical Engineering. 115, 1205-1226.

Daniel, D.E., Trautwein, S., Boynton, S. & Foreman, D. 1984. Permeability Testing with Flexible-Wall Permeameters. Geotechnical Testing Journal, 7, 3, 113-122.

D'Arcy, H.P.G. 1856. Les fontaines publiques de la ville de Dijon. Dalmont, Paris.

Deb, S.K. & Shukla, M.K. 2012. Variability of hydraulic conductivity due to multiple factors. American Journal of Environmental Science, 8 (5), 489 – 502.

Dingman, S.L. 1984. Fluvial Hydrology, xv + 383 pp. New York: W. H. Freeman.

Dixon, N. & Bromhead, E.N. 1999. Depth dependent permeability in London Clay measured using standpipe piezometer equilibration data. Géotechnique, 49, 5, 651-660.

Dyer, M., Utili, S. & Zielinski, M. 2009. Field survey of desiccation fissuring of flood embankments. Proceedings of the Institute of Civil Engineers: Water Management. 162(WM3), 221-232.

Garrett, C. & Wale, J. H. 1985. Performance of embankments and cuttings in Gault Clay in Kent. In From Proceedings of the Symposium on Failures in Earthworks, organised by the Institution of Civil Engineers, held in London, March 6-7, 1985.

Glendinning, S., Hughes, P.N., Helm, P., Chambers, J., Mendes, J., Gunn, D., Wilkinson, P. & Uhlemann, S. 2014. Construction, management and maintenance of embankments used for road and rail infrastructure: implications of weather induced pore water pressures. Acta Geotechnica 9(5): 799.

Glendinning, S., Helm, P.R., Rouainia, M., Stirling, R.A., Asquith, J.D., Hughes, P.N., Toll, D.G., Clarke, D., Powrie, W., Smethurst, J., Hughes, D., Harley, R., Karim, R., Dixon, N., Crosby, C., Chambers, J., Dijkstra, T., Gunn, D., Briggs, K. & Muddle, D. 2015. Research-informed design, management and maintenance of infrastructure slopes: development of a multi-scalar approach. International Symposium on Geohazards and Geomechanics. IOP Conference Series: Earth and Environmental Science, 26(1). DOI: 10.1088/1755-1315/26/1/012005

Harley, R., Carse, L., Lynch, K. & Hughes, D. 2013. An evaluation of strain softening of glacial tills as a result of pore pressure dynamics. GeoMontreal. 66th Canadian Geotechnical Conference Proceedings, Geoscience for Sustainability, Montreal, Editors: Ruel, M. & Sylvain, R., pp.6.

Hight, D.W. 2000. Sampling methods: evaluation of disturbance and new practical techniques for high quality sampling in soils. In VII Congresso Nacional de Geotecnia, Porto (Vol. 3, pp. 1275-1309).

Hughes, P.N., Glendinning, S., Mendes, J., Parkin, G., Toll, D.G., Gallipoli, D. & Miller, P.E. 2009. Full-scale testing to assess climate effects on embankments. Proceedings of the Institute of Civil Engineers: Engineering Sustainability 162. ES2, 67-79.

Hughes, D.A.B., Clarke, G.R.T., Harley, R.M.G. & Barbour, S.L. 2016. The impact of hydrogeology on the instability of a road cutting through a drumlin in the North of Ireland. Quarterly Journal of Engineering Geology & Hydrogeology, 49, 92-104.

Kannangara, D. & Sarukkalige, R. 2011. Geotechnical assessment of soil permeability in land development areas. 2nd International Conference on Environmental Engineering and Application. ICEBEE, 17 106-110.

Lee, D.M., Reynolds, W.D., Elrick, D.E. & Clothier, B.E. 1985. A comparison of three field methods for measuring saturated hydraulic conductivity. Canadian Journal of Soil Science. 65, 563-573

Li, J.H., Zhang, L.M. & Kong, B.C.P. 2011. Field permeability at shallow depth in a compacted fill. Proceedings of the Institution of Civil Engineers – Geotechnical Engineering. 164, GE3, 211-221.

Lili, M., Bralts, V.F. & Yinghua, P. 2008. Methods for measuring soil infiltration: State of the art. International Journal of Agricultural and Biological Engineering. 1(1), 22–30.

Loveridge, F.A., Spink, T.W., O'Brien, K.M., Briggs, K.M. & Butcher, D. 2010. The impact of climate and climate change on infrastructure slopes, with particular reference to southern England. Quarterly Journal of Engineering Geology and Hydrogeology. 43, 461-472.

Merva, G.E. 1987. The velocity permeameter technique for rapid determination of hydraulic conductivity in-situ. In Proceedings of the International Workshop on Land drainage 3rd . Columbus. Ohio State University. 7-11

Mohanty, B.P., Kanwar, R.S., & Everts, C.J. 1994. Comparison of Saturated Hydraulic Conductivity Measurement Methods for a Glacial-Till Soil, Soil Science Society of America Journal. 58(3), 672-677.

Nagy, L., Tabácks, A., Huszák, T. & Varda, G. 2013. Comparison of permeability testing methods. Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris, 399- 402.

Nyambayo, V.P., Potts, D.M. & Addenbrooke, T.I. 2004. The Influence of permeability on the stability of embankments experiencing seasonal cyclic pore water pressure changes. Advances in Geotechnical Engineering. The Skempton Conference. Thomas Telford, London, 898-910.

O'Brien, A., Ellis, E.A. & Russell, D. 2004. Old railway embankment clay fill-laboratory experiments, numerical modelling and field behaviour. In: Jardine, Potts, R.J., Higgins, K.G. (eds) Proceedings. Advances in geotechnical Engineering: The Skempton conference, London 2004, Vol 1. Thomas Telford, London, 241-290.

O'Brien, A. 2013. The assessment of old railway embankments – time for a change? Partial Saturation in Compacted Soils: Géotechnique Symposium in Print 2011. January 2013, 19-32.

Phoon K-K. & Kulhawy, F.H. 1999. Characterization of geotechnical variability. Canadian Geotechnical Journal, 36: 612–624.

Reynolds, W.D. & Elrick, D.E. 1985. In situ measurement of field saturated hydraulic conductivity, sorptivity, and the α-parameter using the Guelph permeameter. Soil Science, 140: 292-302.

Reynolds, W.D. & Elrick, D.E. 1986. A method for simultaneous in-situ measurements in the vadose zone of field saturated hydraulic conductivity, sorptivity, and the conductivity pressure head relationship. Ground Water Monitoring. 6, 84-89.

Ridley, A., McGinnity, B., & Vaughan, P. 2004. Role of pore water pressures in embankment stability. Proceedings of the ICE-Geotechnical Engineering, 157(4), 193-198.

Rose, C.W. 1966. Movement of Water in Soils, In The Commonwealth International Library: Physics Division. In: Agricultural Physics, edited by Rose, C.W., Pergamon, 160-177.

Sinnathamby, G., Phillips, D., Sivakumar, V. & Paksy, A. 2014. Landfill cap models under simulated climate change precipitation: Impacts of cracks and root growth. Géotechnique, 64(2), 95-107.

Smethurst, J.A., Clarke, D. & Powrie, W. 2006. Seasonal changes in pore water pressure in a grass covered cut slope in London Clay. Géotechnique. 56, 523-537.

Smethurst, J.A., Clarke, D. & Powrie, W. 2012. Factors controlling the seasonal variation in soil water content and pore water pressures within a lightly vegetated clay slope. Géotechnique. 62(5) 429-446.

Springman, S.M., Jommi, C. & Tesseire, P. 2003. Instability on moraine slopes induced by loss of suction: a case history. Géotechnique. 53(1), 3-10.

Springman, S.M., Askarinejad, A., Casini, F., Friedel, S., Keinzler, P., Teysseire, P. & Thielen, A. 2012. Lessons learnt from field tests in some potentially unstable slopes in Switzerland. Acta Slovenica Geotech. 1, 5-29.

Take, W. A. & Bolton, M. D. 2011. Seasonal ratcheting and softening in clay slopes, leading to first-time failure. Géotechnique 61, No. 9, 757–769.

Van Genuchten, M. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America, 44, 5, 892-898.

Vaughn, P.R., Kovacevic, N. & Potts, D.M. 2004. Then and now: some comments on the design and analysis of slopes and embankments. In: Jardine, Potts, R.J., Higgins, K.G. (eds) Proceedings. Advances in geotechnical Engineering: The Skempton conference, London 2004, Vol 1. Thomas Telford, London, 241-290.

Xue, J. & Gavin, K. 2007. Effect of rainfall intensity on infiltration into partly saturated slopes. Geotechnical and Geological Engineering. 26(2), 199-209.

Youngs, E.G., Leeds-Harrison, P.B. & Elrick, D.E. 1995. The hydraulic conductivity of low permeability wet soils used as landfill lining and capping material: analysis of pressure infiltrometer measurements.

Table and Figure captions

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Fig. 7. Hydraulic conductivity (m/s) vs Depth (m) measurements at Newbury, Loughbrickland and Craigmore cuttings

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Fig. 9. Site specific soil moisture deficit (SMD; units of mm) and volumetric water content readings; both plotted with time for the Newbury site. The periods during which hydraulic conductivity tests were carried out are marked by the vertical bars.

Table 1. *Summary site descriptions and hydraulic conductivity test methods employed*

Site	Type /vegetation	Age of Structure	Predominant materials	Operator	Test methods	No. of tests
Newcastle (BIONICS)	Trial – Embankment/ Grasses	<10 years	Glacial till (PI = 16%), capped with a 0.5 metre coarse gravel	Newcastle	Guelph / single cell	85
Laverton, Gloucestershire	Rail – Embankment/ Mature trees and bushes	>100 years	End tipped local Charmouth Mudstone (PI = 30-40%)	Queens / Bath / BGS	Guelph / Double Ring	8
Charing, Kent	Rail –Embankment/ Mature trees and shrubs	>100 years	Gault Clay (PI = 35%), Industrial ash	Southampton / Mott MacDonald	Guelph	4
Newbury, Hampshire	Road – Cutting/ Grasses and shrubs	<20 years	London Clay (PI = 35%)	Southampton	Double Ring / Guelph / single cell / Bail	23
Craigmore, Northern Ireland	Rail – Cutting/ Grasses and shrubs	>100 years	Glacial till deposits (PI = 12-17%)	Queens, Belfast	Guelph	11
Loughbrickland, Northern Ireland	Road – Cutting/ Grasses and shrubs	<10 years	Glacial till deposits (PI = 16-25%)	Queens, Belfast	Guelph	12

Table 2. *Summary of hydraulic conductivity measurements for BIONICS embankment and Newbury, Loughbrickland and Craigmore cuttings*

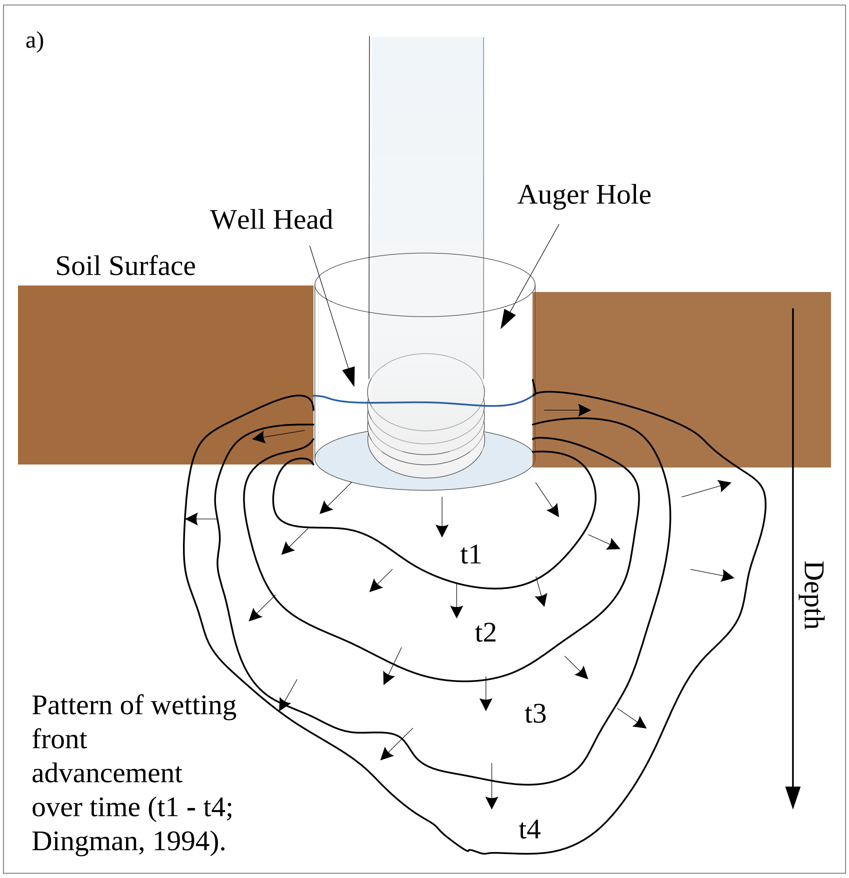
Site	No. of tests	Mean m/s	Max m/s	Min m/s	SD*	CoV^x
BIONICS (all)	85	$3.3x10^{-6}$	$9.6x10^{-5}$	$3.6x10^{-10}$	$1.2x10^{-5}$	3.69
Well compacted$^+$	34	$3.6x10^{-6}$	$4.5x10^{-5}$	$1.1x10^{-9}$	$1.1x10^{-5}$	2.92
Poorly compacted$^+$	51	$3.1x10^{-6}$	$9.6x10^{-5}$	$3.6x10^{-10}$	$1.3x10^{-5}$	4.28
North facing$^+$	49	$4.7x10^{-6}$	$9.6x10^{-5}$	$3.6x10^{-10}$	$1.6x10^{-5}$	3.36
South facing$^+$	36	$1.4x10^{-6}$	$1.3x10^{-5}$	$8.1x10^{-10}$	$3.1x10^{-6}$	2.20
Loughbrickland	12	$1.0x10^{-5}$	$8.6x10^{-5}$	$2.4x10^{-9}$	$2.4x10^{-5}$	2.35
Craigmore	11	$1.0x10^{-6}$	$9.4x10^{-6}$	$3.8x10^{-9}$	$2.7x10^{-6}$	2.57
Newbury$^\$$	18	$1.1x10^{-6}$	$7.3x10^{-6}$	$1.0x10^{-11}$	$2.1x10^{-6}$	1.93

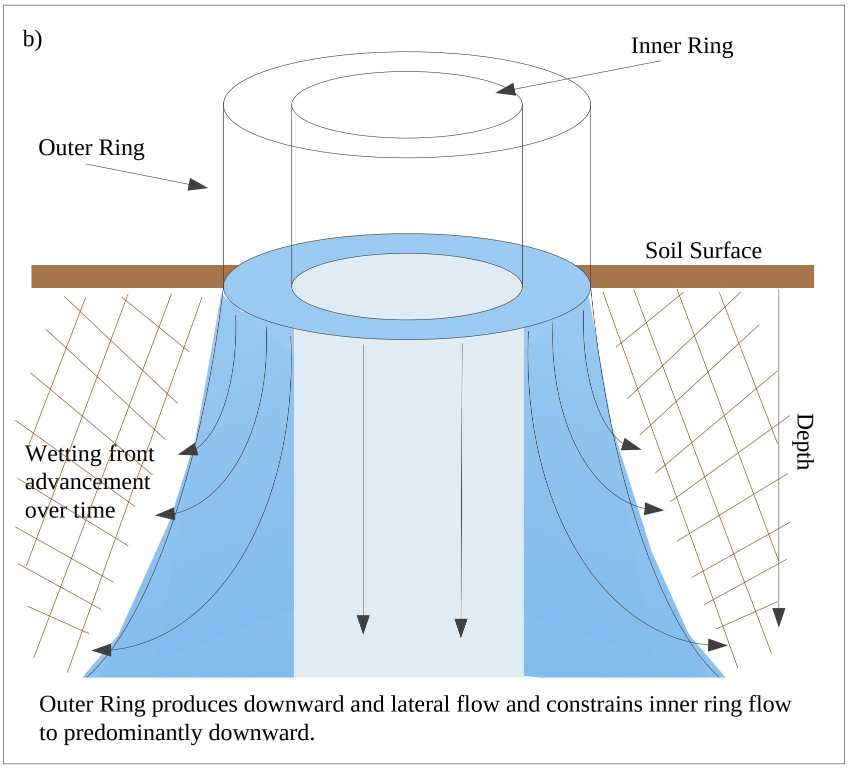
*SD = Standard deviation

^{x}CoV = Coefficient of variation (Standard deviation/Mean)

+ Note that the entire BIONICS data set is reported in the ‘compaction’ and ‘slope orientation’ statistics, hence the repetition of max and min values.

$^\$$ Newbury data set only includes measurements shallower than 1.0m below ground level





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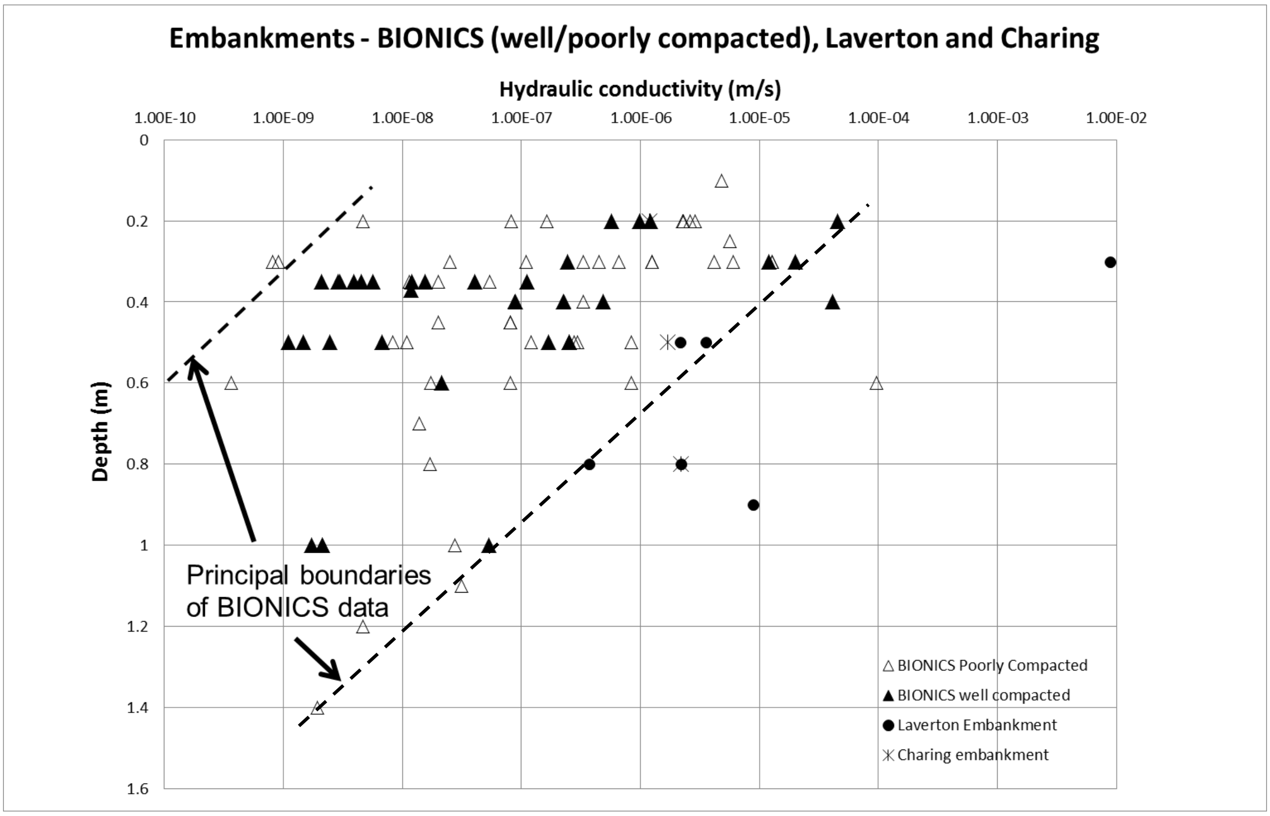

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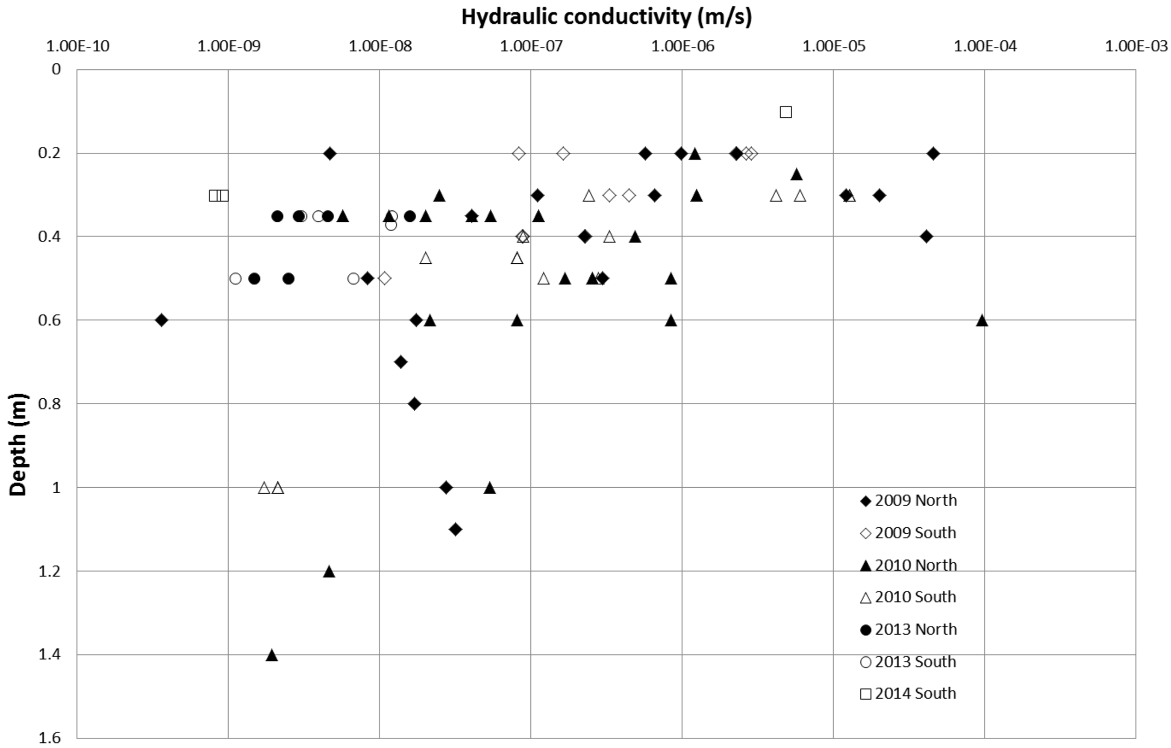

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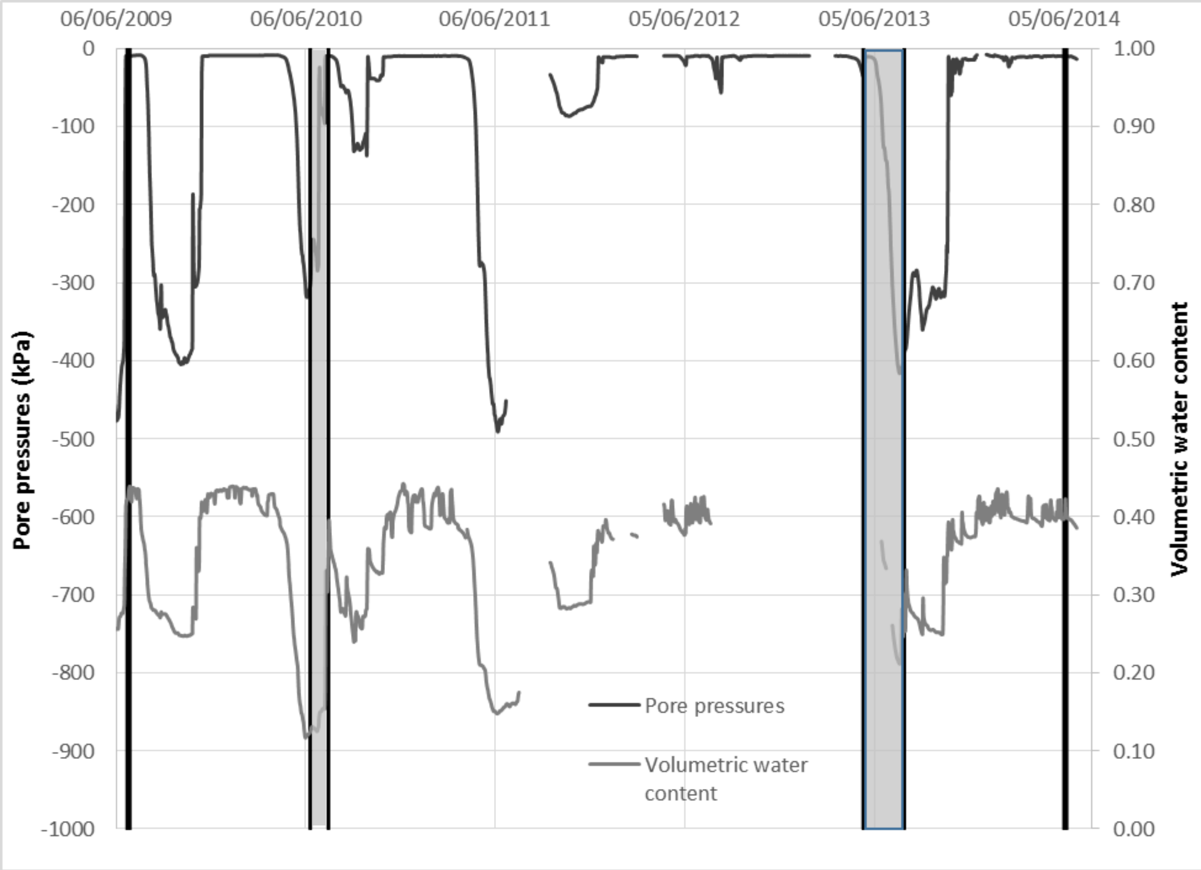

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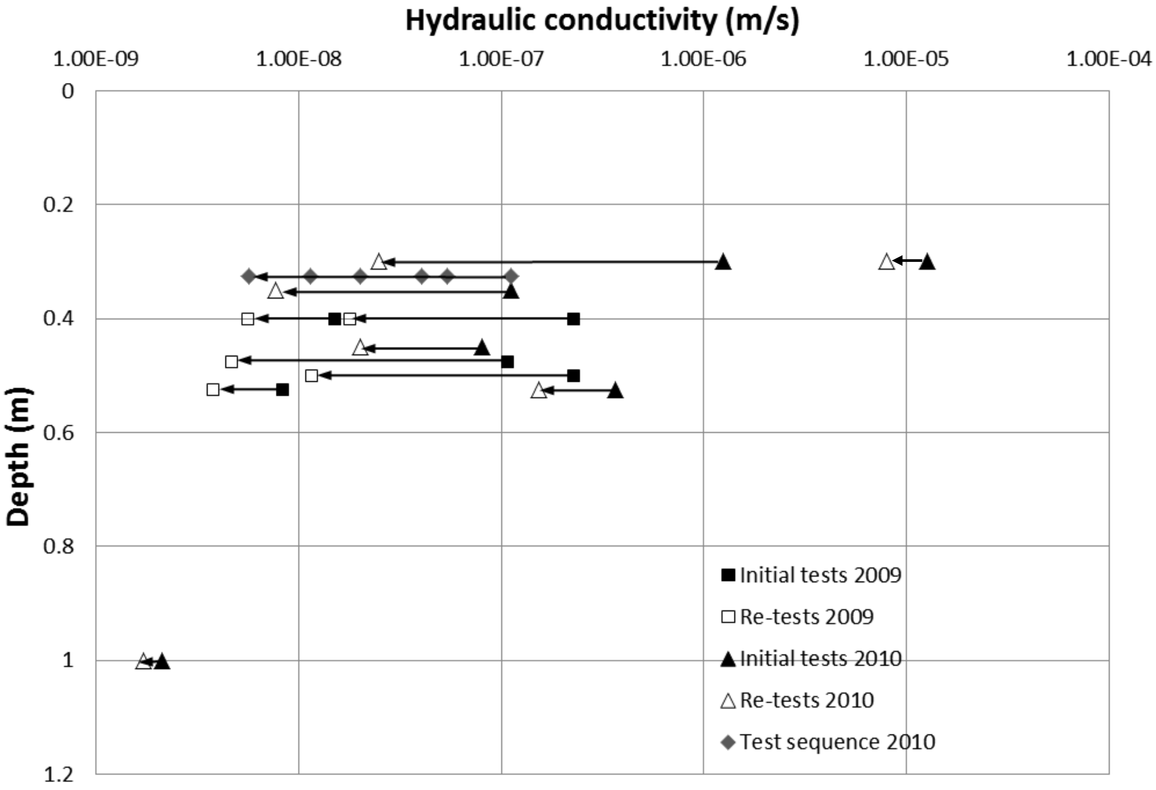

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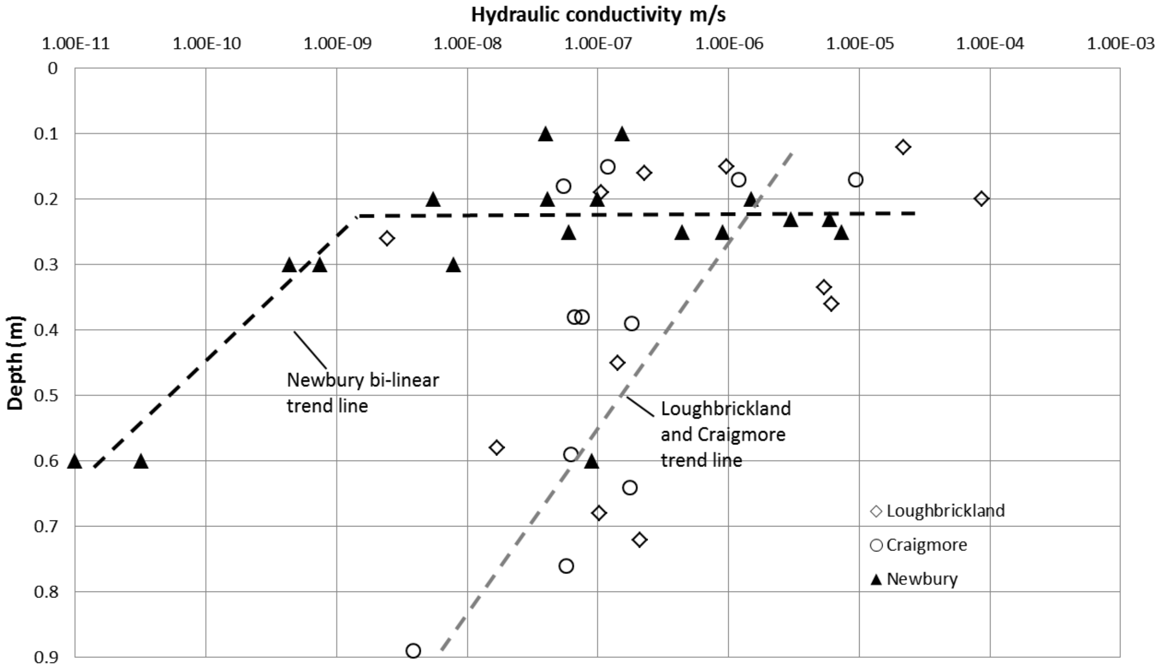

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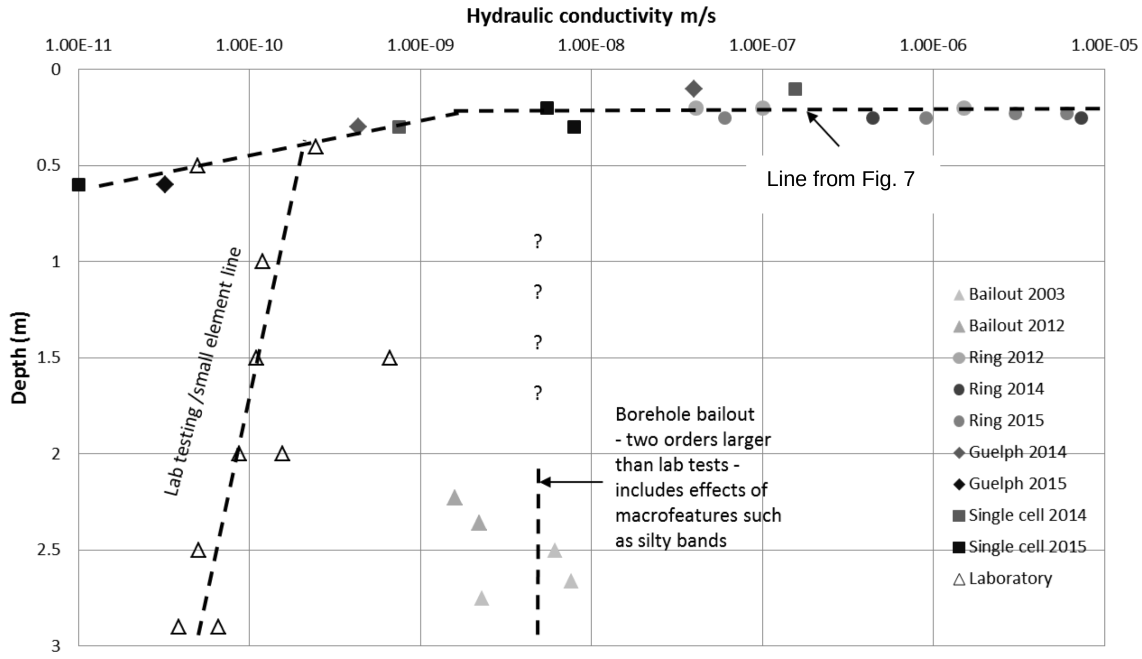

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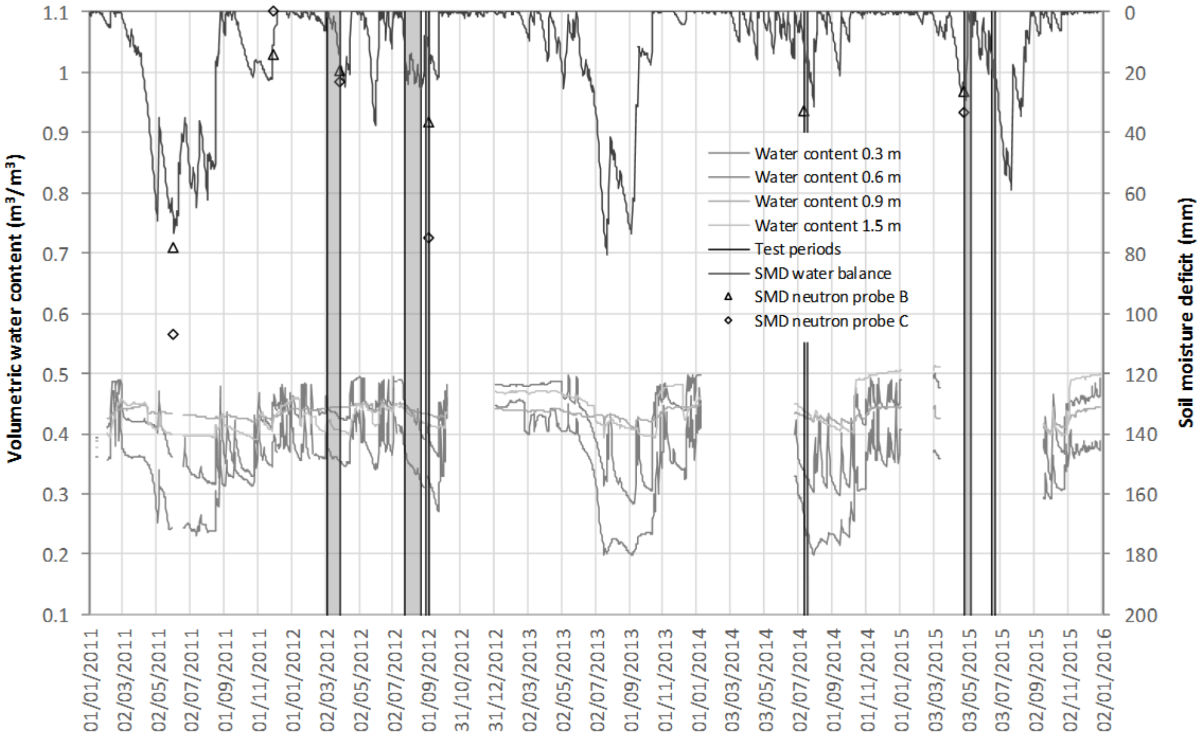

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